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Physical Structure and Circulation in Honokohau, a Small Hawaiian Harbor Affected by Groundwater[1]

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ABSTRACT: Observations of physical structure and circulation are reported and analyzed. Groundwater discharges into the harbor are large and dominate an unusual circulation pattern that produces excellent flushing. A simple numerical model is used to determine residence times, which are found to be of order 12 hr.

THIS PAPER PRESENTS OBSERVATIONS of the physical structure and circulation in the waters of the harbor at Honokohau, Hawaii. The picture is based on measurements made during an intensive field program and is augmented by a simple computer model designed to study flushing characteristics.

Honokohau Harbor is a small, artificial berthing facility on the west coast of the island of Hawaii, a few miles north of Kailua. It is relatively simple in plan shape, and, since it was excavated out of the coastal lava, it has vertical walls. Strong flows of brackish water enter the landward basin through bottom springs, which are concentrated most heavily in the northeast corner (Figure 1). The spring water originates as rainfall on inland mountain slopes. It percolates toward the coast through porous lava structures, mixing with seawater that has entered the porous rock near the coast, and exits as brackish water (17–26 ‰) through springs and seepages.[3] In the harbor, the bottom spring inflow rate is greater than the tidal exchange rate and causes pronounced layering and a vigorous circulation.

The harbor is interesting because it is strongly layered and has an unusual circulation pattern. Moreover, the small size of the basin and its shape provide a relatively good chance to make measurements and understand the processes in the system. The study of Honokohau Harbor might also provide information useful to investigations of other harbor sites where island groundwater flows produce brackish springs near the coast. Brackish outflows are not uncommon along coasts of Hawaii, for example, and similar but weaker seepage occurs in the barge harbor near Barbers Point on Oahu. Since the spring flow and its effects are pronounced at Honokohau, the study might serve as a guide to processes occurring in similar but more complicated settings.

FIELD CONDITIONS

Field conditions during the study period (23 February to 1 March 1975) were typical of those prevailing most of the year. The locality experiences prevailing onshore wind during the day, which increases to 8–10 knots in the afternoon. However, because of the small size of the harbor and the sheltering effect of its vertical walls, there is no appreciable wind-driven circulation. Rainfall was negligible during the study. Coastal surf was 1–2 ft high, except on 27 February, when it rose to about 4 ft and declined again by the next day. The study was timed to coincide with a period of spring tides so that tidal effects would be most apparent.

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[3] Bienfang (1980) contains a further discussion of this hydrology and an aerial infrared photograph showing the strong, cold groundwater discharge in the area prior to harbor construction.

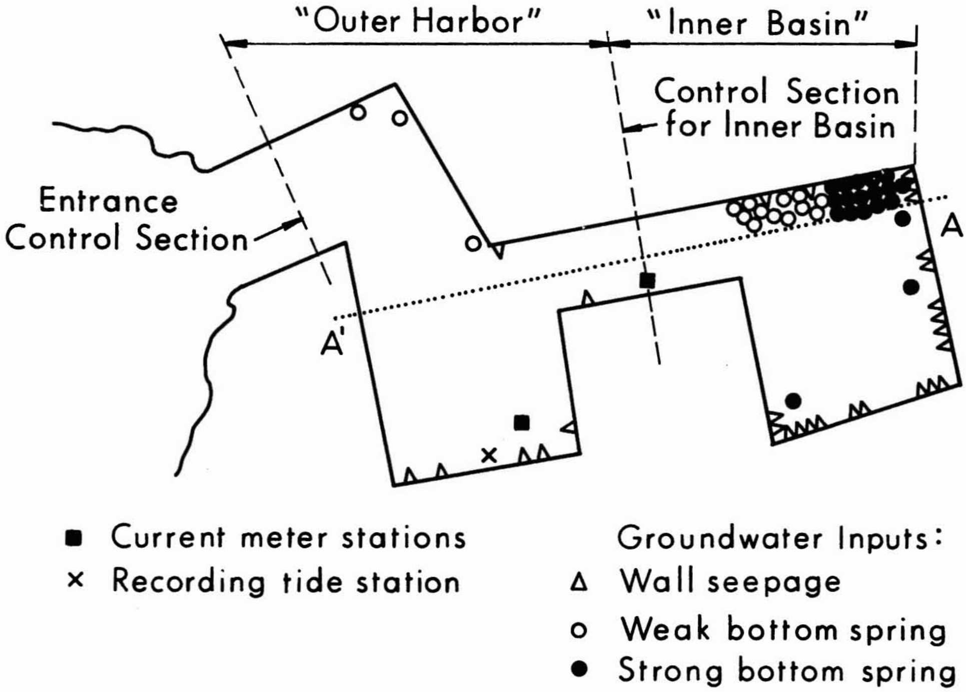


FIGURE 1. Harbor plan map, with locations of certain observations, locations of sections, and approximate positions of groundwater input.

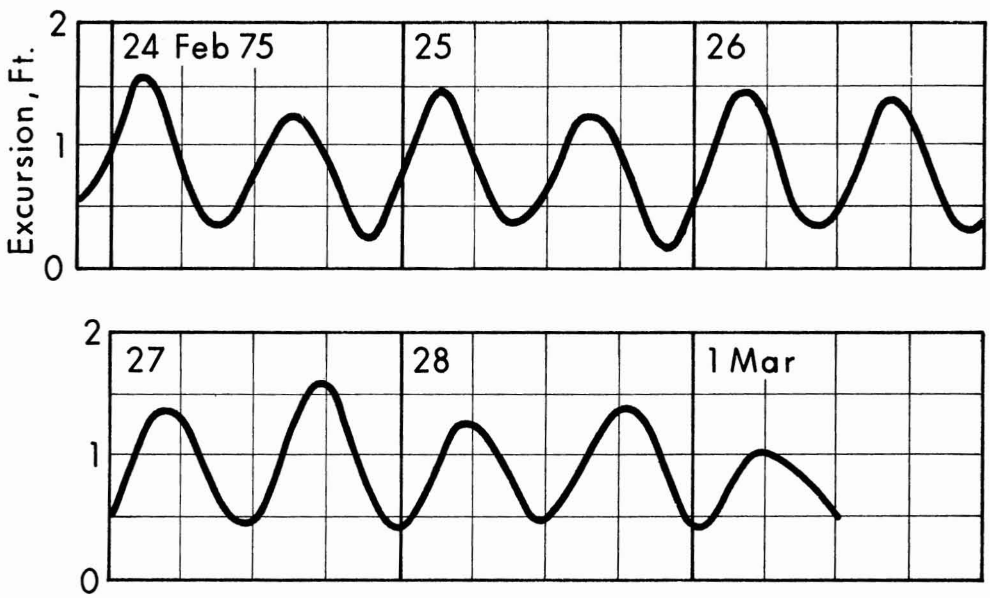


FIGURE 2. Observed tide during study period.

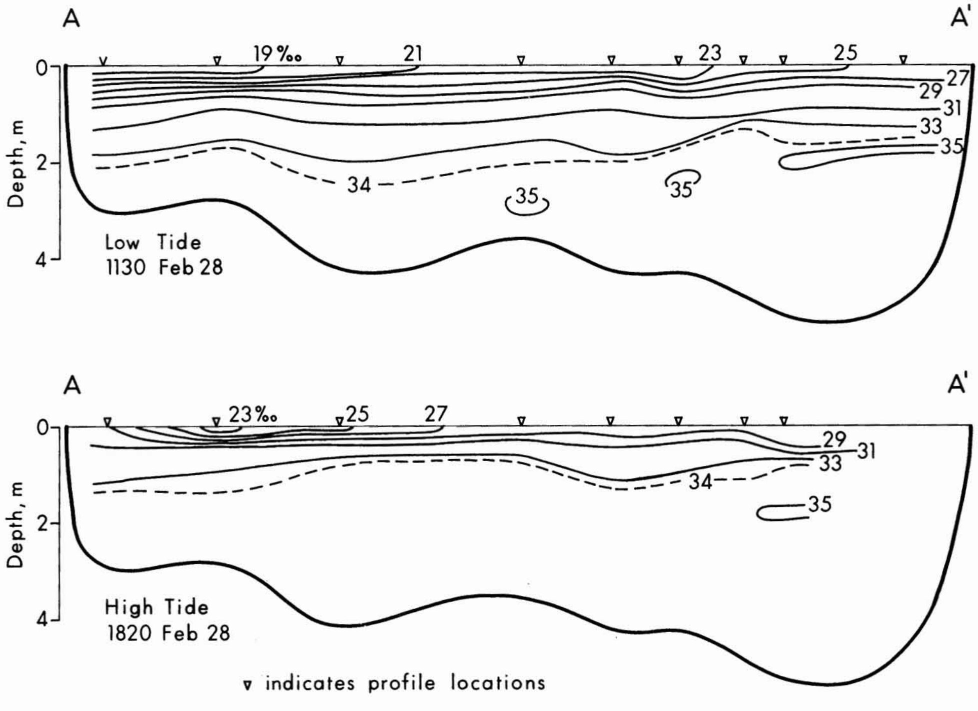


FIGURE 3. Salinity section A–A′.

The recorded tide (Figure 2) had a range of about 1.25 ft, and showed only a diurnal inequality. The water level was recorded every 15 min at the location shown in Figure 1. [The record would also be a good representation of the shoreline tide outside the harbor; the dimensions of the harbor and entrance channel are such that the tide suffers no appreciable attenuation or delay in propagating into the harbor (Gallagher and Munk 1971).]

OVERVIEW

The harbor is essentially a two-layer system. Warm, high-salinity water originating from seawater makes up the lower layer, and a mixture of seawater and cold, brackish spring water forms an upper layer $\frac{1}{2}$–2 m thick. This vertical structure was sampled intensively at both high and low tide with a battery-powered CSTD at 37 stations spaced uniformly throughout the harbor. The vertical sampling interval was 25 cm. The structure can be seen clearly in a salinity section (Figure 3). Temperature structure (not shown) is very similar; water of oceanic origin (24–25°C) underlies a distinct surface layer (20.5–22°C).

The harbor has an unusual circulation pattern that produces excellent flushing. The bottom spring water in the back basin rises through and mixes with water from the lower layer, producing a large volume of surface water that continually flows out of the harbor. Deep water is constantly supplied to replace what has mixed and flowed out at the surface; an effective pumping action is created that draws deep water into the back basin. This pattern of deep inflow and surface outflow dominates the circulation. It is modified by the tide, but its main features persist throughout the tidal cycle.

For measurement, we divided the harbor into two parts: the inner basin and outer harbor, with the boundary midway along the channel connecting the two berthing basins

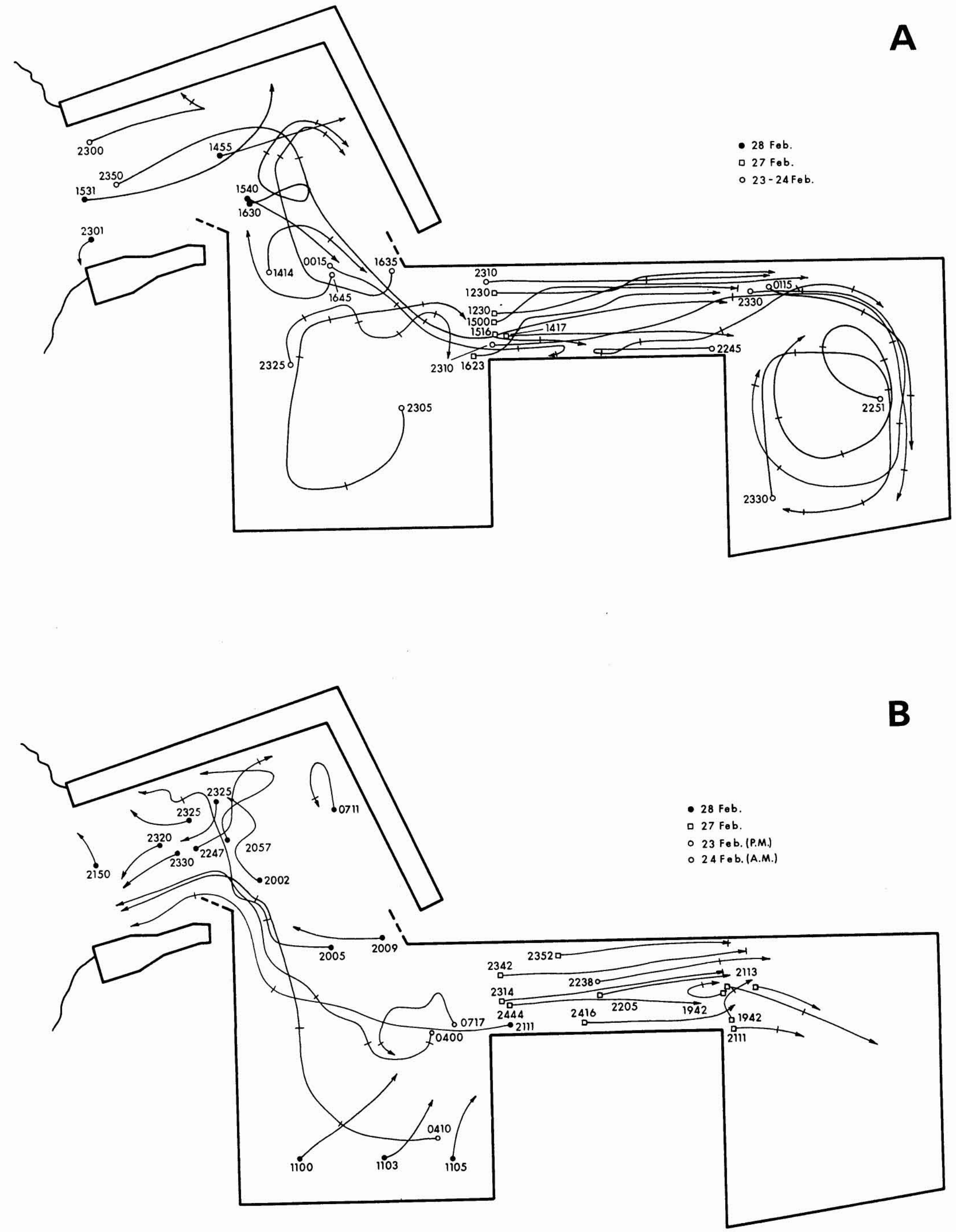
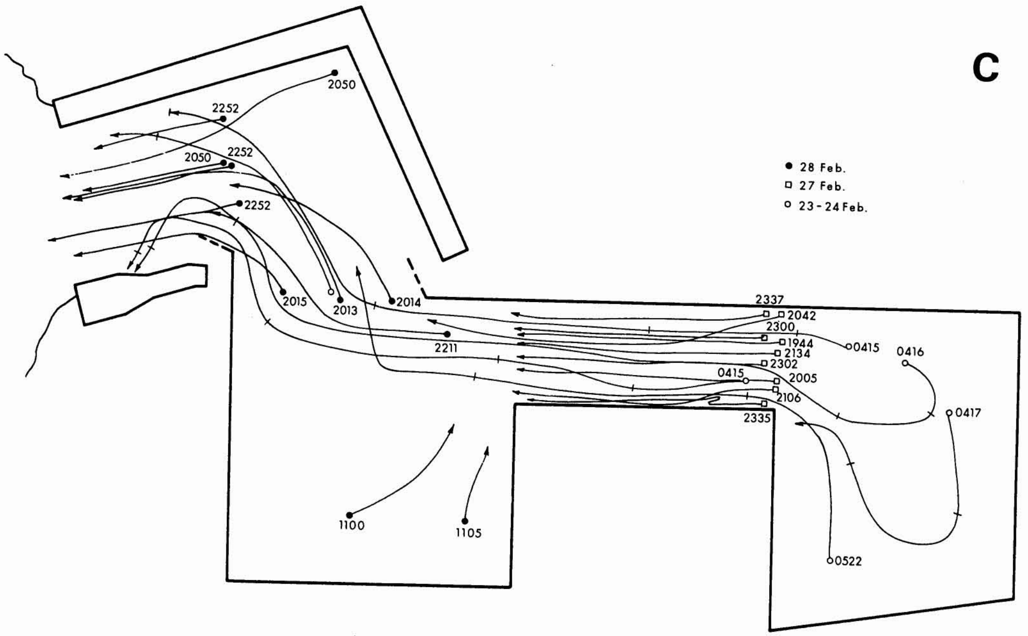


FIGURE 4. Drogue trajectories. *A*, deep layer, rising tide; *B*, deep layer, falling tide; *C*, surface layer, falling tide; *D*, surface layer, rising tide. Ticks denote hours past indicated start times.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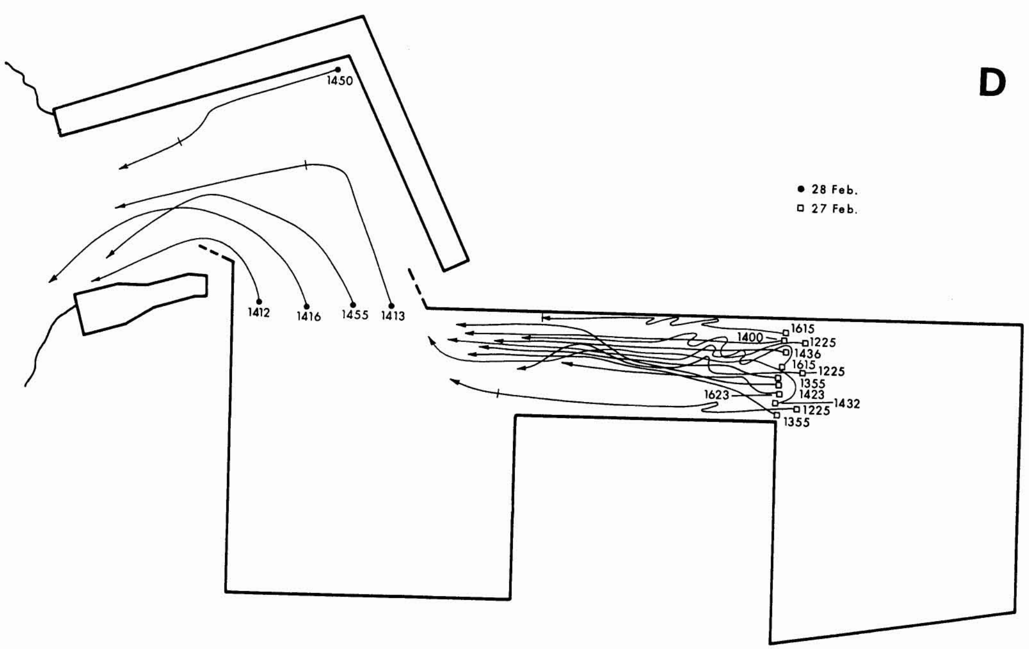
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(Figure 1). Fluxes into and out of the back basin were monitored at this boundary over the period 11:30–24:30 on 27 February, covering one complete flood and ebb cycle. Similar observations were repeated across the main harbor entrance channel over the flood and ebb cycle 11:30–24:30 on 28 February. Weather on these two days was the same, and the tidal patterns were quite similar. We feel that it is justified to assume the behavior of the harbor was very nearly the same on these two days, and so we have combined the data sets in constructing a composite picture.

Fluxes were monitored by taking hourly salinity profiles in each channel while ebb and flood currents were being measured. A current meter (Hydroproducts/Savonius rotor and vane) was employed, but was not generally useful for flux measurements. While the meter was helpful in locating the depth of flow reversal between the two layers, the mean flow speeds were generally less than 5 cm/sec—below the threshold of reliable instrument response. Further, harbor surging imposed variable, reversing currents on the mean flow, making short-duration readings unreliable. (Day-long records made with the current meter fixed 1 m above the bottom at locations shown in Figure 1 showed a prominent surge period of 2 min.) Drogues (2-ft-square current crosses) proved to be best for monitoring mean flows. Ten were deployed simultaneously and repeatedly, producing over 100 trajectories (Figure 4*A–D*).

INNER BASIN

During flood tide, deep water flows into the back basin and increases the depth of the lower layer (Figure 3). Drogue trajectories show that some of this water penetrates directly from the ocean, although mixing reduces the salinity below 35‰. The deep inflow concentrates along the northern side of the interconnecting channel and has a mean speed of about 2.3 m/min. Its average salinity is 34.6‰, and it flows in at a computed mean rate of 63 m^3/min.

There is strong surface outflow from the back basin during the flood tide. The mean surface current speed is 1.8 m/min in the interconnecting channel, and the estimated transport rate is 122 m^3/min. The outflowing water extends down to 1.75 m and has a mean salinity of 29.2‰.

Salt and water budgets permit computation of the discharge rate and salinity of the brackish spring water. Since tidal volume of the back basin increased at the mean rate of 12 m^3/min, the springs were producing at a combined estimated rate of 71 m^3/min. The computed salinity of their waters is 25.3‰. Diver-sampled salinities in the mouths of several springs (25.01, 17.65, 26.45, 26.67‰) are consistent with the computed estimate, providing a rough check on the flux calculations.

Note that tidal flow is only a small part of the total flux into the back basin on rising tide. The mean lower-layer inflow rate is about five times greater than would be required simply to raise the water level. The bulk of the entering water recirculates and leaves the basin again in the strong surface current. The numbers indicate a vigorous upward entrainment of lower-layer water, and we speculate that this occurs mostly at the sites of the brackish bottom springs. It appears that the springs create, in effect, a pumping mechanism that greatly enhances flushing.

During ebb tide, the basic flow pattern through the interconnecting channel remains the same as during flood, but it becomes more vigorous. As the tide falls, the surface layer thickens slightly to 2 m and flows outward more rapidly, with a mean speed of 2.8 m/min. The computed mean outflow rate is 217 m^3/min—nearly twice the flood tide value. Lower-layer inflow increases correspondingly, broadening to occupy about half the channel width and accelerating to a mean speed of 2.7 m/min. Water and salt flux budgets now give 70 m^3/min and 24.4‰ for the flow rate and salinity of the brackish spring water.

The observed flows and computed rates given above represent mean values pertaining to the midpoints of rising and falling

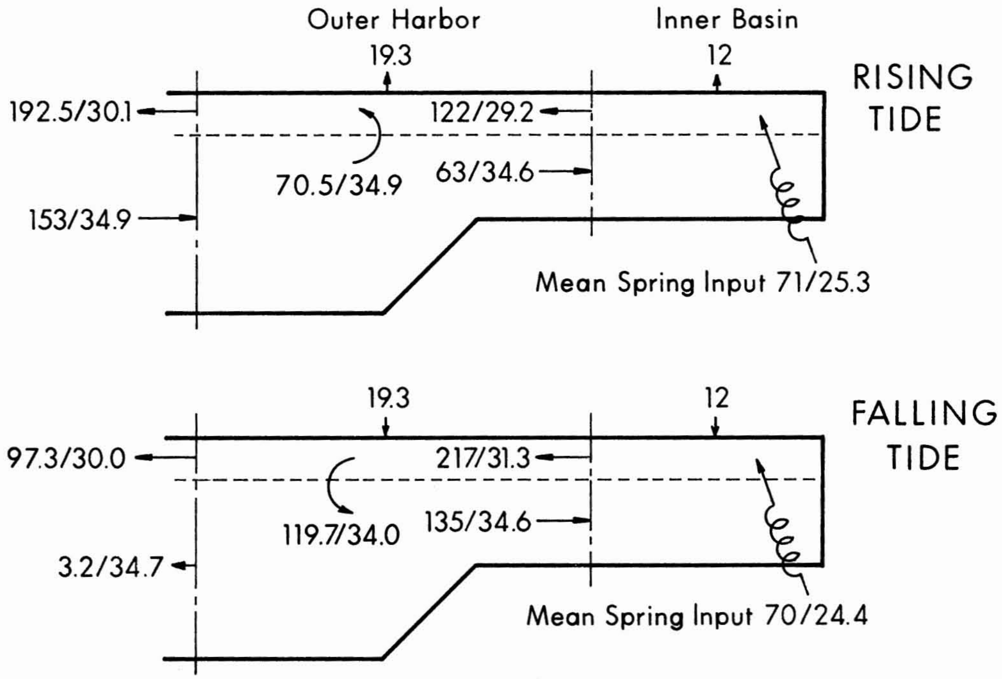

FIGURE 5. Flow schematics. Numbers above slashes are mean volume flow rates (m^3/min); numbers below slashes are mean salinities; numbers with arrows at surface give mean tidal volume gain or loss rates.

tides. They are shown schematically in Figure 5. It is noteworthy that the fluxes to and from the back basin are significantly stronger during the falling tide. We are unsure of the mechanisms that cause this. The observed phenomena suggest that surface outflow from the back basin is partially restricted during flooding tide, and that the rate of spring water outflow may be inversely related to the tidal height. The salinity sections show a greater volume of brackish water present at low tide. Our observations are inadequate to describe or explain these temporal variations in the behavior of the harbor, and additional measurements would be interesting.

OUTER HARBOR

The most prominent circulation feature in the outer harbor is the continuous outflow of surface water emanating from the inner basin. Deep water flows continuously from the outer harbor into the back basin, but there is not a consistent inflow of deep water into the harbor from the ocean. On rising tide there is a significant deep influx, but on falling tide the movement of deep water through the harbor entrance is erratic and sluggish. During this time, the lower layer appears to be resupplied by water mixed downward from the surface layer.

Direct input of brackish water seems negligible in the outer harbor. Diver explorations and salinity sections revealed no bottom springs similar to those present in the back basin. Small, surface seepages can be detected visually around the edges of the outer harbor, but the salinity sections show that these have no appreciable effect. It is a reasonable approximation to neglect direct brackish input.

An important factor in the outer harbor circulation is the exchange of water between upper and lower layers. This can be seen in Figure 3; the salinity of the upper layer increases as the surface water flows outward toward the harbor entrance. The volume of this exchange and the mean salinity of the net exchange are unknowns that remain to be computed.

Volume transports in the entrance channel are less reliably known than in the interconnecting channel. This is primarily because the flow in the lower layer was very irregular. During flood tide, two drogues moved in through the entire length of the entrance channel (Figure 4*A*); however, several others moved in erratic patterns, and we did not feel confident that we had a reliable measurement of the net flow. During ebb tide the deep flow was very slow and again inconsistent (Figure 4*B*), with some drogues moving into the harbor and others leaving. The surface drogues showed a continual outflow (Figure 4*C*, *D*), but we had trouble measuring its thickness. We did not consider the observations good enough for reliable estimates of volume fluxes in the entrance channel.

Our approach to the outer harbor fluxes was to employ simultaneous salt and volume budgets, using observed values for the variables that had been measured most reliably and computing the others. The most reliable observations were those of the fluxes into and out of the back basin, the time history of salinity in the entrance channel, and the salinity sections for high and low tide. From these data we were able to estimate mean salinities for the flows through the entrance and rates of salt accumulation or loss for each layer in the outer harbor, and could then calculate the interlayer exchange and the entrance channel volume fluxes. In these calculations, it was necessary to choose some boundary between the upper and lower layers. The depth of the 33‰ salinity surface was suggested by our observations in the interconnecting channel, and using this guide we chose the interlayer boundary at a depth of 1 m everywhere except in the entrance channel at ebb tide, where the 33‰ surface indicated that 0.5 m was more suitable. A check on the calculations is provided by comparison of observed and computed surface outflow speeds.

The following picture emerges for the outer harbor and is shown schematically in Figure 5: During flood tide, water in the lower layer enters the harbor at a mean rate of 153 m^3/min. A small part of this raises the tidal level of the outer harbor (19.3 m^3/min). Another fraction replaces water that has been entrained in the outflowing surface layer (70.5 m^3/min). The mean salinity of this flux is calculated at 34.9‰, which agrees with the observed salinity of lower-layer water. The rest of the deep inflow replaces water that is entering the back basin (63 m^3/min). In the surface layer, there is a flux from the inner basin of 122 m^3/min. As this surface water moves across the outer harbor, its volume is increased by net exchange from the lower layer so that 192.5 m^3/min leave through the harbor entrance. The mean salinity of the surface outflow is increased from 29.2‰ to 30.1‰ by the addition of the saltier water from below. The above numbers allow the calculation of mean surface outflow speed (3.7 m/min) and deep inflow speed (0.9 m/min), and these are consistent with drogue movements.

During ebb tide, the outer harbor develops a stronger recirculation pattern in response to the more vigorous flow of deep water into the back basin. Lower-layer water flows into the back basin at 135 m^3/min, and the bulk of this is resupplied within the outer harbor by a net exchange from the upper layer (119.7 m^3/min). The calculated mean salinity of this supply is 34.0‰, which is consistent with the salinity observed at the bottom of the upper layer at high tide. If we assume that the tidal drop (19.3 m^3/min) is due to loss of water from the lower layer, the budget calculations indicate a very small lower-layer outflow through the entrance channel (3.2 m^3/min).

In the surface layer during ebb tide, the continuous outflow is decreased by recirculation to the lower layer so that of the 217 m^3/min which enter from the back basin, only 97.3 m^3/min leave through the entrance channel. The loss of salt is reflected in a mean salinity reduction from 31.3‰ to 30.0‰. Computing outflow speeds in the entrance channel, we get 3.8 m/min and 0.02 m/min for the upper and lower layers, respectively; these are consistent with the drogue observations.

ASSESSMENT OF THE FLUX BUDGETS

We need to consider briefly how accurate the above picture is and how well it may represent general conditions. Observed quantities such as flow speeds and layer depths might be inaccurate by 10–20 percent, and derived quantities such as the spring inflow rate could be off by, perhaps, 40 percent. The description of the basic structure and behavior of the harbor is qualitatively correct. Numerical values are, at worst, order-of-magnitude estimates.

A remaining question is whether the observed behavior is typical. The answer depends strongly on whether the submerged spring input rates were typical or unusual during the study period. The strength of the flow probably depends on the recent history of rainfall on the adjacent mountain slopes, but we find no studies on the response of these coastal seepages to weather conditions. It is usual for the springs to be active, because the local harbor users report that the surface layer outflow is a permanent condition. It further seems reasonable that the spring input rate does not often decrease by an order of magnitude, because the resulting surface outflow would probably not be noticeable to the local boaters. Thus, we speculate that the rate of 70 m^3/min is a typical order of magnitude for the spring output. Then, as seen above, the tidally driven components of the flow are of secondary importance; the picture developed for a period of spring tides would be roughly the same during neap tides as well. During the study period, the weather was typical for the area, but the observed harbor behavior could be greatly modified by strong local winds and heavy rain.

HORIZONTAL CIRCULATION WITHIN THE HARBOR

The horizontal circulation is best described by the drogue tracks (Figure 4*A*–*D*). There are many irregular, random motions in the harbor, but a general, overall pattern is present. During flood tide, deep water enters the harbor and joins two large-scale eddying motions—one in the elbow of the entrance channel and one in the outer berthing basin. There is strong flow through the inner channel, with the momentum of the water creating a large clockwise eddy in the back basin. The eddying motions in the deep water have dimensions comparable to the berthing basins, and speeds such that water takes on the order of 6 hr to make one cycle. As the tide is falling, the same pattern of deep flow persists in the inner basin, but the two large eddies in the outer harbor appear to break down into smaller, irregular motions, with a weak net outflow to the ocean.

The surface flow pattern is relatively simple. Water persistently streams outward along the main axis of the harbor. Within the berthing basins it appears that the eddying motions of the deep layer are transmitted to the surface water. No significant change of pattern was observed from flood to ebb tide.

FLUSHING AND RESIDENCE TIMES

The harbor is flushed exceptionally well, and this is due directly to the existence of the strong flow of brackish water from springs in the floor of the back basin. Because the springs are in the innermost part of the harbor, they affect the entire harbor. The bulk of the inflow through the harbor bottom tends to maximize the amount of mixing between the brackish water and water in the lower layer of the harbor. The process produces a larger volume of surface water, a larger surface outflow, and a much larger deep inflow than would occur if the brackish input were near the surface. The effects of the brackish springs are important also because of their large flow rate; volume exchange in the inner basin is about ten times what it would be if it were due to tidal action alone and six times larger for the harbor as a whole.

A second factor in the flushing is the sequenced channel-and-basin configuration. The channels accelerate the flows. These in turn produce circulating motion within the basins, helping to prevent the development of stagnant areas.

These factors aided the development of a simple model to study flushing behavior. The harbor was divided into segments, each of which might be reasonably well mixed internally during a half tidal cycle. Known fluxes between segments (including the time-varying tidal effects) were employed, and the network of interconnected segments was modeled numerically. Concentrations of dissolved substances were then simulated by stepping the model network through time.

The observed eddy patterns tend to divide the harbor into three main parts, each of which would be fairly well mixed internally: the inner basin, the outer basin, and the entrance channel. (In this scheme, the boundary between the inner and outer basins is at the midpoint of the interconnecting channel; a line that is the extension of the north wall of this channel forms the boundary between the outer basin and the entrance channel.) The upper and lower layers of each section were considered separately, so that a total of six interconnected segments was used in the model. Ebbing and flooding tide volume fluxes between segments and at the harbor mouth were taken as those presented earlier, and the fluxes at other times were computed by assuming a semidiurnal sinusoidal variation between these values. The spring flow was assumed constant. The single free parameter in the model designated how much of the total vertical exchange in the outer harbor occurs in the outer basin and how much of it occurs in the entrance channel.

The model was checked by specifying the salinity of the deep inflow at the entrance and that of the brackish spring influx; allowing the model to run through many tidal cycles until a steady, periodic salinity was obtained in all six sections of the model; and then comparing these salinities with observed mean values from the harbor itself. Good agreement was obtained, and it was best when the vertical, interlayer exchange in the outer harbor was confined to the outer basin (i.e., no vertical fluxes in the entrance channel).

The model was used to simulate the fate of a hypothetical pollutant spill in each of the six harbor segments. In each case, it was assumed that a quantity of dissolved material was introduced by some initial event in one harbor segment, and that it took one tidal cycle to become dispersed locally within that segment of the harbor. The pollutant was then followed as it moved through all harbor segments, and the history of its mean concentration in each segment was computed. In every case, the pollutant was introduced at low tide, since this produces the longest residence times.

Each of the six simulated cases produced generally similar results. Contaminant put into the lower layer of the outer basin remains in the harbor longest, and this case is shown as an example (Figure 6). The concentration dies exponentially in the deep outer basin; the material subsequently enters other harbor areas and then again decays exponentially. The surface layers of the outer basin and entrance channel display two concentration peaks, corresponding to the direct introduction of material by vertical transport within the outer basin and a later introduction of material that has first circulated through the inner basin. Peak concentration in the deep inner basin reaches about 40 percent of the initially dispersed value in the deep outer basin. The surface layers all reach about 25 percent of this, while the deep layer of the entrance channel experiences only about 1 percent.

The simulations allow estimates of residence times for each harbor segment. Throughout the harbor, advection is so rapid that the greatest part of the residence time for a spill in any location is the period required for its initial dispersion within that harbor segment (estimated from the drogue studies to be about 12 hr). Once the material has dispersed locally and begins to be transported by the larger-scale flows through the harbor, it is flushed out quite rapidly; after advection takes effect the mean concentration drops to half its original value in less

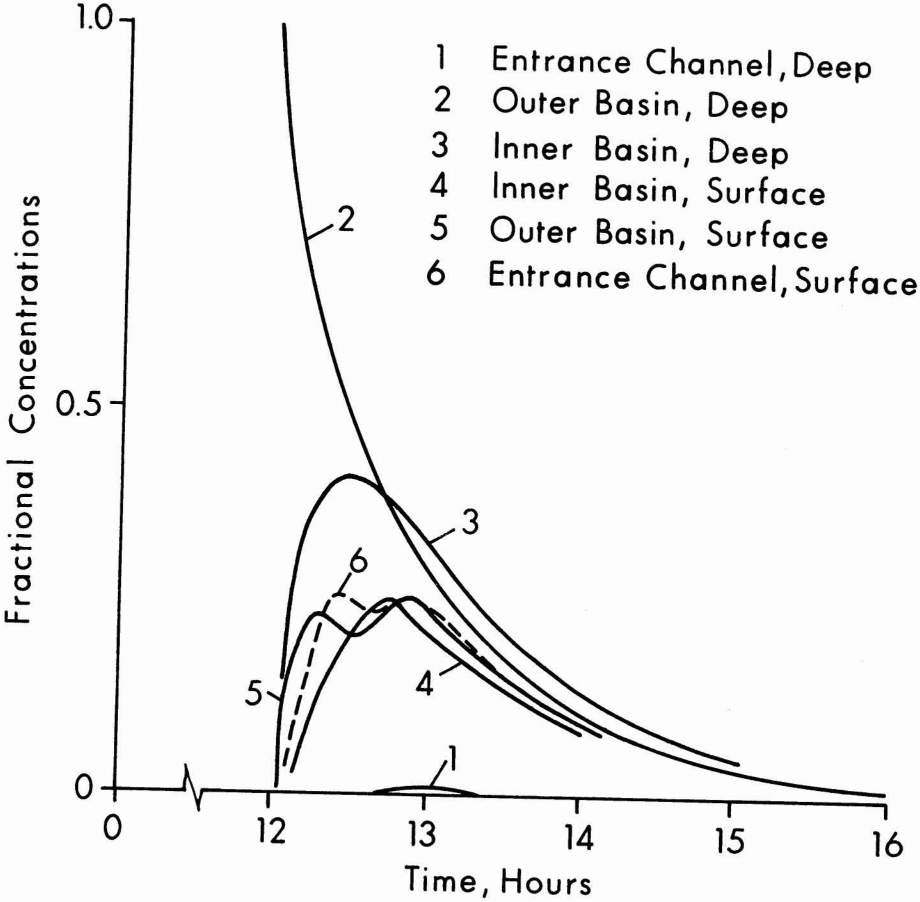

FIGURE 6. Time history of pollutant concentration in each harbor segment. The pollutant resulted from an initial spill in the lower layer of the outer harbor basin; it was assumed to take 12 hr to disperse locally before entering into convective transports.

than an hour in all harbor segments. The half-life of a contaminant in any harbor segment, and in the harbor as a whole, is 12–13 hr.

LITERATURE CITED

BIENFANG, P. 1980. Water quality characteristics of Honokohau Harbor: A subtropical embayment affected by groundwater intrusion. Pac. Sci. 34(3): 279–291.

GALLAGHER, B., and W. MUNK. 1971. Tides in shallow water: Spectroscopy. Tellus 23:346–363.